RESEARCH MEMORANDUM

ALTITUDE INVESTIGATION OF 20-INCH-DIAMETER RAM-JET

ENGINE WITH ANNULAR-PILOTED COMBUSTOR

By James G. Henzel, Jr., and Arthur M. Trout

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Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
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SUMMARY

As part of a general research program on ram-jet combustors, an investigation of the performance of a 20-inch-diameter ram-jet engine having an annular-piloted combustor was conducted at zero angle of attack in a facility utilizing both the free-jet and direct-connect techniques. A comparison was also made with other combustors recently investigated. Data were obtained at a simulated flight Mach number of 3.0 over a range of combustor-exit total pressures from about 570 to 2400 pounds per square foot absolute.

A dual fuel-injection system provided high combustor efficiencies, generally above 0.80, over a range of fuel-air ratios from 0.015 to 0.08. Combustor efficiency decreased with pressure from 0.97 at 2370 pounds per square foot absolute to 0.76 at 570 pounds per square foot absolute. At 1/3 atmosphere, a combustor efficiency of 0.82 was obtained. Decreasing combustor length from 87 to 57 inches decreased combustor efficiency from 9 to 12 percentage points.

The comparison of the annular-piloted combustor with two other combustors of different design showed that all three combustors had about the same specific fuel consumption over the whole fuel-air-ratio range. The specific fuel consumption of the annular-piloted combustor was slightly higher than the best configuration at fuel-air ratios from 0.015 to 0.050 and slightly lower than the other configurations at fuel-air ratios greater than 0.050.

INTRODUCTION

As part of a research program being conducted at the NACA Lewis laboratory to determine design criteria for ram-jet combustors suitable for long-range missiles, the performance of an annular-piloted combustor has been evaluated. The annular-piloted combustor is one of five combustors that have been studied in the 20-inch-diameter ram-jet engine program. The four other combustors investigated included an annular-gutter flame

holder with a low-heat-release central pilot, an annular-gutter and a sloping-gutter flame holder with a high-heat-release central pilot, and a can-type flame holder with a low-heat-release central pilot. Results of the investigations of these combustors are reported in references 1 to 3, respectively.

Reference 4 shows that an annular-piloted combustor gave combustion efficiences and combustor total-pressure ratios in excess of 0.90 at low fuel-air ratios in a 48-inch-diameter ram-jet engine. A similar combustor was accordingly built and investigated in the 20-inch-diameter ram-jet engine to provide performance and design data directly comparable to the four combustors previously subjected to extensive development in the 20-inch ram-jet program.

The combustor efficiency, combustor-inlet Mach number, and combustor total-pressure ratio of the annular-piloted combustor are presented herein. The effect of combustor-exit total pressure on combustor efficiency, the effect of decreasing combustor length on combustor efficiency, and a comparison of configurations on the basis of specific fuel consumption are also presented.

APPARATUS

Engine

A schematic sketch of the 20-inch-diameter ram-jet engine is shown in figure 1. The supersonic diffuser is of the double-cone annular type utilizing two oblique shocks and one normal shock. The subsonic diffuser was divided into three channels by the inner body supports. The combustion chamber, 87 inches in length for most of the investigation, was water-jacketed and had an inside diameter of 20 inches. For part of the investigation, the combustor length was shortened to 57 inches. The engine was equipped with a contoured water-jacketed convergent exhaust nozzle having a throat area equal to 55 percent of the combustion-chamber area. The fuel used in the engine and the preheater, which is subsequently discussed, was MIL-F-5624A grade JP-4.

Combustor Configuration

Flame holder. - The design of the annular-piloted combustor (fig. 2) was based on the results of references 4 and 5. In cross section, the shape of the annular-piloted combustor was that of an asymmetric V. The outer surface, perforated by three rows of 1/2-inch-diameter holes, was extended downstream to act as a flow divider and to provide a protected combustion zone. The inner surface of the annular-piloted combustor was

cut longitudinally in 18 places, and the cuts were spread at the down-
stream end by forming the metal into V-shapes; the resulting openings
provided additional air entry for pilot combustion and permitted a gradual
mixing of the main-stream fuel-air mixture with the pilot combustion pro-
ducts. An annular-gutter, with a mean diameter of $7\frac{5}{32}$ inches, was attached
to the trailing edge of the inner surface of the annular pilot. A fuel-
mixing control sleeve 15.1 inches in diameter was attached to the leading
edge of the asymmetric V to provide two separate zones of fuel injection
and mixing in order to maintain locally a favorable fuel-air mixture for
combustion at low over-all fuel-air ratios.

Fuel system. - The fuel for the annular-piloted combustor was in-
jected in three locations, in the pilot, in the inner zone, and in the
outer zone. The pilot fuel system was located at the base of the asym-
metric V (fig. 2(a)) and contained five equally spaced spray bars. Each
bar had two 0.040-inch-diameter holes spraying downstream at an angle of
45° to the combustor center line. The inner- and outer-zone fuel systems
(fig. 2(a)) were located 12.1 and 7.7 inches upstream of the annular pilot
and contained 15 equally spaced spray bars having two 0.062-inch-diameter
holes per bar, spraying perpendicular to the engine air flow.

All fuel spray bars had an external metering orifice to prevent
plugging of the bars (fig. 2(a)). The metering orifices were 0.021,
0.032, and 0.040 inch in diameter for the pilot, inner-zone, and outer-
zone fuel spray bars, respectively, and were relatively easy to service.

Test Facility

The test facility, which was operated both by the free-jet and direct-
connect techniques, is shown schematically in figure 3. The air, which
entered the facility through a combustion-type preheater, was vitiated
to a fuel-air ratio of 0.009 or less. For free-jet operation, the air
passed into a surge tank and was expanded through a convergent-divergent
nozzle to a Mach number of 3.0. The engine inlet was submerged in the
Mach number 3.0 jet at zero angle of attack and the excess air spilled
around the inlet through the jet diffuser. The engine exhaust passed
into a separate chamber which could be throttled for engine starts. A
more detailed description of the free-jet facility and its operation is
given in reference 6.

The method used to convert the facility to a direct-connect type is
illustrated schematically in the auxiliary view of figure 3. Blank-off
plates covered the jet diffuser so that the air was ducted subsonically
to the annulus formed by the engine cowl lip and the engine diffuser.
The direct-connect facility was the same as that used in reference 3.

Instrumentation

The locations of temperature and pressure instrumentation at the various stations are shown in figures 1 and 3. Wall static pressure was measured near the engine subsonic-diffuser exit (fig. 1, station 2). A water-cooled rake (fig. 1, station 4) just upstream of the engine exhaust-nozzle inlet provided a total-pressure survey for use in air-flow and combustor-efficiency calculations. Engine fuel flow was measured by calibrated rotameters. The inlet total pressure and temperature were measured in the surge tank upstream of the supersonic nozzle (fig. 3, station 0) and were used to establish simulated engine flight conditions. Combustion could be viewed looking upstream through the engine exhaust nozzle by means of a periscope.

PROCEDURE

Simulated Flight Conditions

The total temperature of the air entering the surge tank was raised to 1100° R by means of the combustion-type preheater to simulate the standard total temperature for flight at Mach number 3.0 above the tropopause. For free-jet operation, the total pressure in the surge tank was varied to provide a range of air flows from 10.11 to 3.42 pounds per second per square foot of combustion-chamber cross-sectional area (hereinafter referred to as unit air flow). This range of unit air flows corresponds to simulated altitudes from 61,800 to 84,400 feet, respectively. The engine, because of its inlet and exit geometry, operated supercritically for all fuel-air ratios. Combustion-chamber pressures are therefore considerably lower for the simulated altitudes of this investigation than are obtainable with critical operation of the inlet. The performance is therefore presented both in terms of unit air flow and in terms of corresponding simulated altitudes. The direct-connect data were obtained at a unit air flow of 6.88.

Method of Engine Operation

With air flow and inlet temperature set, the exhaust-throttling valve (fig. 3) was partly closed to raise the pressure level and reduce the velocities in the combustor sufficiently to ignite the pilot burner by means of a spark plug. Fuel flow to the inner zone was initiated, and a fuel-air ratio of about 0.02 established. The exhaust-throttling valve was opened and the engine exhaust nozzle choked. The pilot-burner fuel flow was held constant at a fuel-air ratio of 0.005 or less as the inner-zone fuel flow was varied to obtain the performance at the low fuel-air ratios (inner-zone operation). The inner-zone and pilot burner fuel

3377

value (maximum combustor efficiency) as fuel flow to the outer zone was varied to obtain the performance at the high fuel-air ratios (outer-zone operation).

Calculations

The engine fuel-air ratio was calculated as the ratio of engine fuel flow to the unburned air flow entering the engine. The combustor efficiency was taken as the ratio of ideal to actual fuel-air ratio, where the ideal fuel-air ratio was that necessary to obtain, with an ideal combustion process, the total pressure measured at the exit of the engine combustion chamber for the air flow under consideration. The specific fuel consumption was calculated as the ratio of the engine fuel flow in pounds per hour to the net thrust in pounds.

The symbols are listed in appendix A. The methods used to calculate engine air flow, engine fuel-air ratio, combustor efficiency, combustor-inlet Mach number, and specific fuel consumption are outlined in appendix B.

RESULTS AND DISCUSSION

Performance Characteristics

Combustor efficiency. - Free-jet performance data obtained with the annular-piloted combustor are presented in figure 4, wherein combustor efficiency, combustor-inlet Mach number, and combustor-exit total pressure are plotted against engine fuel-air ratio. The data are presented for unit air flows of 10.11, 6.88, 5.48, 4.11, and 3.42 (pounds per second per square foot of combustion-chamber cross-sectional area). In figure 4(a), it can be seen that, in general, for a given unit air flow, the combustor efficiency with inner-zone operation increased rapidly as fuel-air ratio increased, reached a maximum, and then diminished gradually. As unit air flow decreased from 10.11 to 3.42, the maximum combustor efficiency decreased from 0.86 to 0.76 and simultaneously shifted to somewhat richer fuel-air ratios. The shift in maximum combustor efficiency to richer fuel-air ratios was a result of the deterioration of the lean-stability limit with decreasing unit air flow.

Similar to inner-zone operation, the combustor efficiency with outer-zone operation increased rapidly as fuel-air ratio increased, reached a maximum, and then diminished gradually. Maximum combustor efficiency decreased from 0.97 to 0.81 as unit air flow decreased from 10.11 to 3.42. The dual fuel-injection system provided good combustor efficiencies over a wide range of fuel-air ratios, generally 0.80 for fuel-air ratios from 0.015 to 0.08.

A simultaneous variation in combustor-inlet Mach number with com-
bustor efficiency occurred as the fuel-air ratio varied. From figure
4(b), it can be seen that combustor-inlet Mach number decreased from
0.23 at a fuel-air ratio of 0.015 to 0.15 at a fuel-air ratio of 0.08
and was independent of unit air flow.

At a given fuel-air ratio, variation in combustor efficiency with
unit air flow was due largely to the variation in combustor-exit total
pressure (fig. 4(c)). At lean fuel-air ratios (inner-zone operation),
combustor-exit total pressure varied from about 1860 to 570 pounds per
square foot absolute. At rich fuel-air ratios (outer-zone operation),
combustor-exit total pressure varied from about 2400 to 750 pounds per
square foot absolute.

The effect of combustor-exit total pressure on maximum combustor
efficiency is shown in figure 5, for both inner- and outer-zone operation.
Decreasing combustor-exit total pressure from 1570 to 900 pounds per
square foot absolute decreased the maximum combustor efficiency with
inner-zone operation from about 0.86 to about 0.85. As combustor-exit
total pressure decreased further to 560 pounds per square foot absolute,
however, the maximum combustor efficiency dropped rapidly to 0.76. The
maximum combustor efficiency with outer-zone operation decreased from
0.97 to 0.81 as combustor-exit total pressure decreased from 2370 to 780
pounds per square foot absolute. At 1/3 atmosphere, a combustor effi-
ciency of 0.82 was obtained.

Combustor total-pressure ratio. - The variation in combustor total-
pressure ratio with fuel-air ratio is presented in figure 6 for unit air
flows of 10.11, 6.88, 5.48, 4.11, and 3.42. It can be seen that the
combustor total-pressure ratio is essentially independent of fuel-air
ratio and unit air flow. The average combustor total-pressure ratio
was about 0.95. Reference 1 indicated that a V-gutter flame holder with
a projected blockage of 55 percent had a combustor total-pressure ratio
of 0.87 at a fuel-air ratio of 0.02. Although the annular-piloted com-
bustor had a projected blockage of 48 percent, nearly as much as for the
typical V-gutter flame holder, the annular-piloted-combustor total-
pressure ratio was considerably higher (0.95, compared with 0.87 at a
fuel-air ratio of 0.02). The superiority of the annular-piloted com-
bustor over that of the V-gutter flame holder of about the same projected
blockage is attributable to the fact that the annular-piloted flame
holder geometry is distributed axially rather than in a single plane.

Effect of Length on Combustor Efficiency

The effect of shortening the annular-piloted combustor configuration
from 87 to 57 inches is shown in figure 7. Combustor efficiency is

3377

plotted against engine fuel-air ratio for a unit air flow of 6.88. The
data for both lengths were obtained by the direct-connect technique. The
maximum combustor efficiency with inner-zone operation was 0.85 for the
87-inch combustor and decreased approximately 9 percentage points to
0.76 for the 57-inch combustor. This decrease in maximum combustor ef-
ficiency with inner-zone operation is about the same as that for the
V-gutter flame holder of reference 1 and slightly less than that for
the can-type flame holder of reference 3. A pronounced shift in the
maximum combustor efficiency with outer-zone operation to a higher fuel-
air ratio occurred as combustor length was shortened. Although a similar
effect was observed with the can-type flame holder (ref. 3), the reasons
for this effect are not clearly understood. The maximum combustor ef-
ficiency with outer-zone operation was 0.90 for the 87-inch combustor
and decreased approximately 12 percentage points to 0.78 for the 57-
inch combustor. Thus the annular-piloted combustor configuration ex-
hibited about the same sensitivity to length as did the V-gutter and
can-type flame holders of references 1 and 3.

It is interesting to note by comparing figure 7 with figure 4(a)
that essentially the same combustor efficiencies were obtained by the
free-jet and direct-connect testing techniques for the 87-inch combustor.
Unpublished NACA data obtained in this facility (zero angle of attack and
symmetrical engine inlet) have shown similar agreement for free-jet and
direct-connect testing techniques.

Comparison of Configurations on Basis of Specific Fuel Consumption

Because the range of a ram-jet-powered aircraft is influenced by
both the combustor efficiency and the combustor total-pressure ratio,
the performance of the annular-piloted combustor, the can-type flame
holder, and the V-gutter flame holder are compared in figure 8 on the
basis of specific fuel consumption. Specific fuel consumption is plotted
against net thrust per pound of air flow for a unit air flow of 6.88.
An over-all diffuser total-pressure recovery of 0.6 was assumed for the
calculation. In addition, a curve indicating the ideal combustor per-
formance (based on a combustor efficiency of 1.0 and the appropriate
pressure loss of heat addition) is also presented for comparison. For
lean operation (fuel-air ratios less than 0.03), the combustors had
about the same performance. The can-type flame holder appeared best
between fuel-air ratios 0.03 and 0.045. For rich operation (fuel-
air ratios greater than 0.05), the annular-piloted combustor had a
slight superiority.

SUMMARY OF RESULTS

An investigation of the performance of a 20-inch-diameter ram-jet
engine having an annular-piloted combustor was conducted at zero angle of

attack in a facility similating flight at Mach number 3.0. Data were obtained with a dual fuel-injection system over a range of fuel-air ratios from about 0.005 to 0.08.

A dual fuel-injection system provided combustor efficiencies generally above 0.80 over a range of fuel-air ratios from 0.015 to 0.08. Combustor efficiency decreased with pressure from 0.97 at 2370 pounds per square foot absolute to 0.76 at 570 pounds per square foot absolute. At 1/3 atmosphere, a combustor efficiency of 0.82 was obtained. Decreasing combustor length from 87 to 57 inches decreased combustor efficiency from 9 to 12 percentage points.

The comparison of the annular-piloted combustor with two other combustors of different design showed that all three combustors had about the same specific fuel consumption over the whole fuel-air-ratio range. The specific fuel consumption of the annular-piloted combustor was slightly higher than the best configuration at fuel-air ratios from 0.015 to 0.050 and slightly lower than the other configurations at fuel-air ratios greater than 0.050.

Lewis Flight Propulsion Laboratory
     National Advisory Committee for Aeronautics
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APPENDIX A

SYMBOLS

The following symbols are used in this report:

A area, sq ft

a local speed of sound, ft/sec

B ratio of engine inlet air flow to supersonic nozzle air flow

C_d discharge coefficient of exhaust nozzle

C_v velocity coefficient of exhaust nozzle

F_n net thrust, lb

f/a engine fuel-air ratio

(f/a)' ideal fuel-air ratio

$(f/a)_p$ preheater fuel-air ratio

$(f/a)_s$ stoichiometric fuel-air ratio

g acceleration due to gravity, 32.2 ft/sec^2

M Mach number

P total pressure, lb/sq ft abs

p static pressure, lb/sq ft abs

R gas constant, (ft)(lb)/(lb)($^\circ$R)

sfc specific fuel consumption $\dfrac{\text{lb fuel/hr}}{\text{lb net thrust}}$

T total temperature, $^\circ$R

t static temperature, $^\circ$R

V velocity, ft/sec

W engine-inlet air flow (containing preheater products of combustion), lb/sec

3377

CJ-2

W_a preheater air flow, lb/sec

$W_{f,e}$ fuel flow to engine (including pilot fuel flow), lb/sec

$W_{f,p}$ fuel flow to preheater, lb/sec

W_u unburned air flow entering engine, lb/sec

γ ratio of specific heats

η combustor efficiency

ρ density, lb/cu ft

Subscripts:

c   cold (engine not burning)

h   hot (engine burning)

0   free stream

2   subsonic diffuser exit

3   conditions at station 2 adjusted to combustion-chamber area

4   exhaust-nozzle inlet

5   exhaust-nozzle minimum area

6   station downstream of exhaust-nozzle exit

APPENDIX B

METHODS OF CALCULATION

Engine air flow. - The engine exhaust nozzle served as a convenient metering orifice for determining the rate of air flow through the engine for nonburning conditions. The engine air flow was calculated from the mass-flow equation

$$W = \rho_{5,c} \, C_{d,c} \, A_5 \, V_{5,c} \tag{1}$$

which was expressed as

$$W = \frac{P_{5,c} C_{d,c} A_5 \sqrt{\gamma_c g}}{\left(\dfrac{\gamma_c + 1}{2}\right)^{\frac{\gamma_c+1}{2(\gamma_c-1)}} \sqrt{RT_{5,c}}} \tag{2}$$

where $P_{5,c}$ and $T_{5,c}$ were assumed equal to $P_{4,c}$ and T_0, respectively. The exhaust nozzle was choked and its discharge coefficient $C_{d,c}$ was assumed to be 0.985. Leakage through the engine flanges was assumed to be negligible.

Engine fuel-air ratio. - The engine fuel-air ratio was defined as the ratio of the engine fuel flow to the unburned air flowing into the combustor. Leaving the preheater was a gas which had a fuel-air ratio of

$$\left(\frac{f}{a}\right)_p = \frac{W_{f,p}}{W_a} \tag{3}$$

where W_a is the preheater air flow measured by an A.S.M.E. flat-plate orifice. It was found that the preheater combustion efficiency was nearly 100 percent. The ratio B of the engine inlet air flow to the supersonic nozzle air flow was constant. The unburned air passing into the engine was then

$$W_u = BW_a \left[1 - \frac{(f/a)_p}{(f/a)_s}\right] \tag{4}$$

This is different from W which contains preheater products of combustion. The engine fuel-air ratio was then

$$\frac{f}{a} = \frac{W_{f,e}}{BW_a \left[1 - \frac{(f/a)_p}{(f/a)_s}\right]} \tag{5}$$

Because it was more convenient to measure the engine inlet air flow W than BW_a, use was made of the following relation:

$$W = B(W_a + W_{f,p}) = BW_a \left[1 + \left(\frac{f}{a}\right)_p\right] \tag{6}$$

Rearranging gives

$$BW_a = \frac{W}{\left[1 + \left(\frac{f}{a}\right)_p\right]} \tag{7}$$

Substitution of equation (7) in equation (5) gives

$$f/a = \frac{W_{f,e}}{W} \left[\frac{1 + (f/a)_p}{1 - \frac{(f/a)_p}{(f/a)_s}}\right] \tag{8}$$

Combustor efficiency. - The combustor efficiency η was defined as

$$\eta = \frac{(f/a)'}{(f/a)} \tag{9}$$

where f/a is given by equation (8) and $(f/a)'$ is the ideal fuel-air ratio which would have produced the same combustor-exit total pressure P_4 as was measured for the burning conditions under consideration. Thus, the efficiency was related only to combustor-exit total pressure, obviating the direct measurement of the high combustion-chamber temperatures.

The determination of $(f/a)'$ was implemented in the following way: Because the engine-inlet diffuser operated supercritically at all times, the entering air flow at a given pressure was the same for the nonburning and burning conditions and could be expressed as

$$W = \rho_{5,c} C_{d,c} A_5 V_{5,c} = \frac{\rho_{5,h} C_{d,h} A_5 V_{5,h}}{1 + \frac{W_{f,e}}{W}} \tag{10}$$

3377

By use of the equation of state, converting static pressure and temperature to total values, converting velocity to Mach number, and rearranging equation (10), the following expressions may be written:

$$P_{5,h} = \frac{W\left(1 + \dfrac{W_{f,e}}{W}\right)}{C_{d,h}A_5 M_{5,h}}\sqrt{\frac{R_h T_{5,h}}{\gamma_h g}}\left(1 + \frac{\gamma_h - 1}{2}M_{5,h}^2\right)^{\frac{\gamma_h + 1}{2(\gamma_h - 1)}} \quad (11)$$

and

$$P_{5,c} = \frac{W}{C_{d,c}A_5 M_{5,c}}\sqrt{\frac{R_c T_{5,c}}{\gamma_c g}}\left(1 + \frac{\gamma_c - 1}{2}M_{5,c}^2\right)^{\frac{\gamma_c + 1}{2(\gamma_c - 1)}} \quad (12)$$

Dividing equation (11) by equation (12), assuming that

$$P_{5,c} = P_{4,c} \quad (13)$$

$$P_{5,h} = P_{4,h} \quad (14)$$

$$T_{5,c} = T_{4,c} = T_0 \quad (15)$$

$$T_{5,h} = T_{4,h} \quad (16)$$

$$C_{d,h} = C_{d,c} \quad (17)$$

and noting that

$$M_{5,c} = M_{5,h} = 1 \quad (18)$$

yields the following equation:

$$\frac{P_{4,h}}{P_{4,c}} = \sqrt{\frac{T_{4,h}}{T_0}}\left(1 + \frac{W_{f,e}}{W}\right)\sqrt{\frac{\left[\left(\frac{\gamma + 1}{2}\right)^{\frac{\gamma + 1}{\gamma - 1}}\left(\frac{R}{\gamma}\right)\right]_h}{\left[\left(\frac{\gamma + 1}{2}\right)^{\frac{\gamma + 1}{\gamma - 1}}\left(\frac{R}{\gamma}\right)\right]_c}} \quad (19)$$

The pressure ratio $P_{4,h}/P_{4,c}$ was then evaluated for various ideal fuel-air ratios by using theoretical combustion charts, which included the effects of dissociation, to find $T_{4,h}$. These data were then plotted as $(f/a)'$ against $P_{4,h}/P_{4,c}$. By referring to this plot, the theoretical fuel-air ratio $(f/a)'$ could be obtained for each value of $P_{4,h}/P_{4,c}$ measured in the engine combustion chamber.

The combustor efficiency as defined herein is not a chemical combustion efficiency such as a heat-balance or enthalpy-rise method would indicate. The combustor efficiency based on total-pressure measurement is more representative of over-all engine performance, as it indicates how effectively the fuel is being used to provide thrust potential rather than how completely the fuel is being burned.

Combustor-inlet Mach number. - The combustor-inlet Mach number was calculated using the engine inlet air flow W, the static pressure measured at station 2 p_2, the ambient total temperature T_0, and the maximum area of the combustion chamber (314.2 sq in.).

Specific fuel consumption. - The specific fuel consumption was calculated as the ratio of the engine fuel flow in pounds per hour to the net thrust. Thus

$$\text{sfc} = \frac{\left(W_{f,e}\right)3600}{F_n} \qquad (20)$$

where the net thrust F_n is given by

$$F_n = \frac{W}{g} V_6 C_v\left(1 + \frac{f}{a}\right) + A_6(p_6 - p_0) - \frac{W}{g} V_0 \qquad (21)$$

By substituting equation (21) into equation (20) and rearranging, equation (20) can be expressed as

$$\text{sfc} = \frac{\left(\dfrac{W_{f,e}}{W}\right)g\ 3600}{V_6 C_v(1 + f/a) + \dfrac{A_6}{W}g(p_6 - p_0) - V_0} \qquad (22)$$

For this expression $W_{f,e}/W$ was considered equivalent to f/a of equation (8). The exhaust gases were assumed to be completely expanded to atmospheric pressure. Therefore, the quantity $(A_6/W)g(p_6 - p_0)$ is zero; C_v was taken as 0.95.

The velocity V_6 was determined as follows:

$$V_6 = M_6 a_6 \tag{23}$$

$$V_6 = M_6 \sqrt{\gamma_6 g R_6 t_6} \tag{24}$$

$$V_6 = M_6 \sqrt{\frac{(\gamma_6 g R_6 T_6)}{\left(1 + \frac{\gamma_6 - 1}{2} M_6{}^2\right)}} \tag{25}$$

The quantity M_6 was determined by the exhaust-nozzle pressure ratio P_4/p_0 as follows:

$$\frac{P_4}{p_0} = \frac{P_2}{p_0} \frac{P_4}{P_2} \frac{P_0}{p_0} \tag{26}$$

where P_2/p_0 was assumed to be 0.60 (readily obtained in practice) for all the data and P_4/P_2 was combustor total-pressure ratio. The ratio P_0/p_0 was 36.7 (a constant corresponding to flight at a Mach number of 3.0).

The temperature T_6 was determined from T_0, the combustor efficiency, engine fuel-air ratio, and a curve of temperature rise against theoretical fuel-air ratio. Thus, all the quantities in equation (25) are determined.

REFERENCES

1. Trout, Arthur M., and Wentworth, Carl B.: Free-Jet Altitude Investigation of a 20-Inch Ram-Jet Combustor with a Rich Inner Zone of Combustion for Improved Low-Temperature-Ratio Operation. NACA RM E52L26, 1953.

2. Henzel, James G., Jr., and Wentworth, Carl B.: Free-Jet Investigation of 20-Inch Ram-Jet Combustor Utilizing High-Heat-Release Pilot Burner. NACA RM E53H14, 1953.

3. Smolak, George R., and Wentworth, Carl B.: Altitude Investigation of Can-Type Flame Holder in 20-Inch-Diameter Ram-Jet Combustor. NACA RM E54D08, 1954.

4. Meyer, Carl L., and Welna, Henry J.: Investigation of Three Low-Temperature-Ratio Combustor Configurations in a 48-Inch-Diameter Ram-Jet Engine. NACA RM E53K20, 1954.

5. Rayle, Warren D., and Koch, Richard G.: Design of Combustor for Long-Range Ram-Jet Engine and Performance of Rectangular Analog. NACA RM E53K13, 1954.

6. Wentworth, Carl B., Hurrell, Herbert G., and Nakanishi, Shigeo: Evaluation of Operating Characteristics of a Supersonic Free-Jet Facility for Full-Scale Ram-Jet Investigations. NACA RM E52I08, 1952.

3377

End of inner
body support

Beginning of inner
body support

Fuel spray bars

Total-pressure
survey rake

Exhaust nozzle

Supersonic diffuser

Dummy probe

Annular-piloted
combustor

A

Air flow

A

(Station 0 is
shown on fig. 3)

Inner body

Station 2

Fuel-mixing
control sleeve

Subsonic
diffuser

3

Combustion
chamber

4   5   6

Assumed flight-
nozzle extension

CD-3686
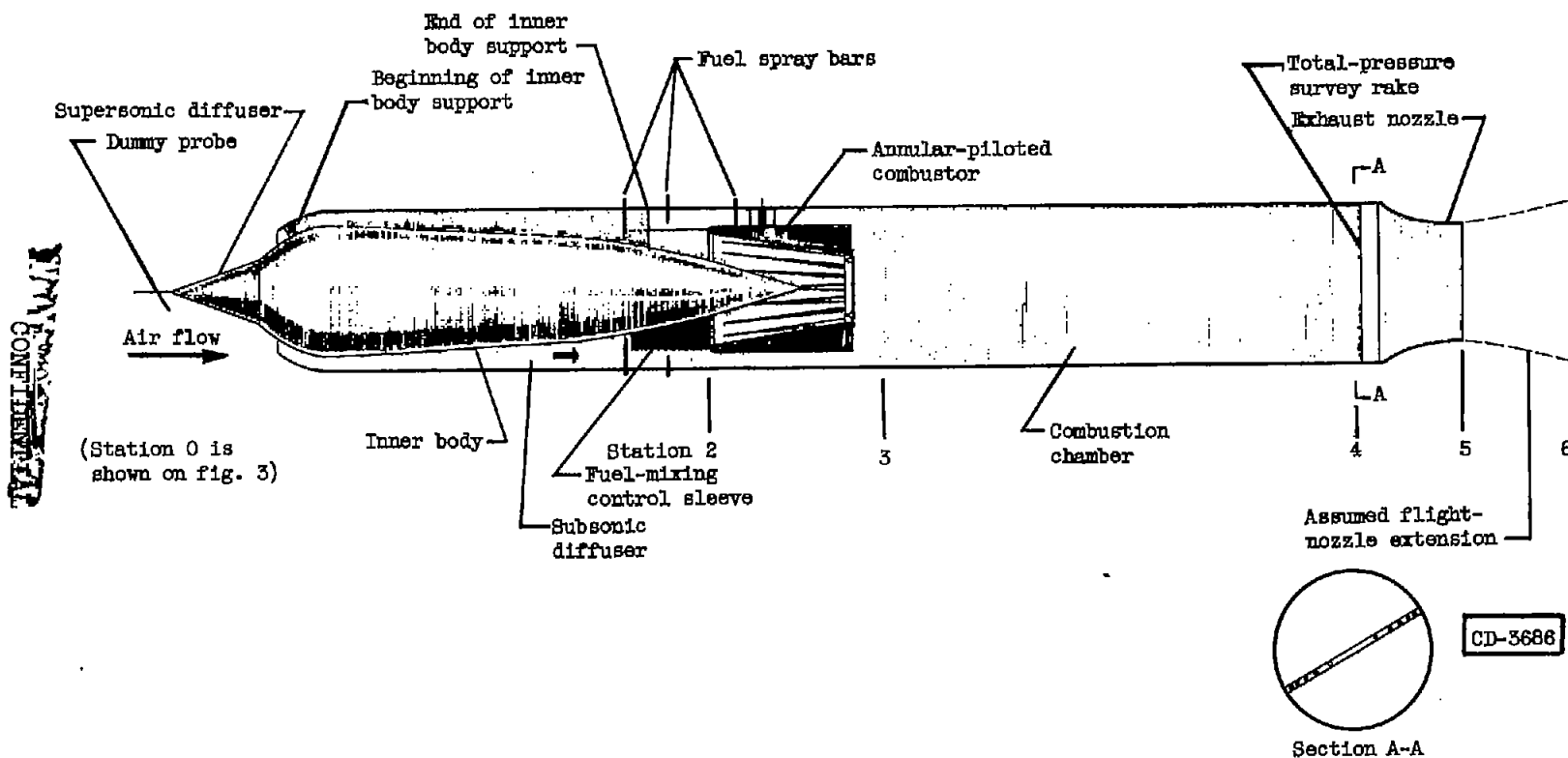
Section A-A

Figure 1. - Cross section of 20-inch-diameter ram-jet engine with annular-piloted
combustor.

Section A-A
Inner-zone fuel system

Section B-B
Outer-zone fuel system

Section C-C
Pilot fuel system

(a) Schematic diagram. (All dimensions in inches.)
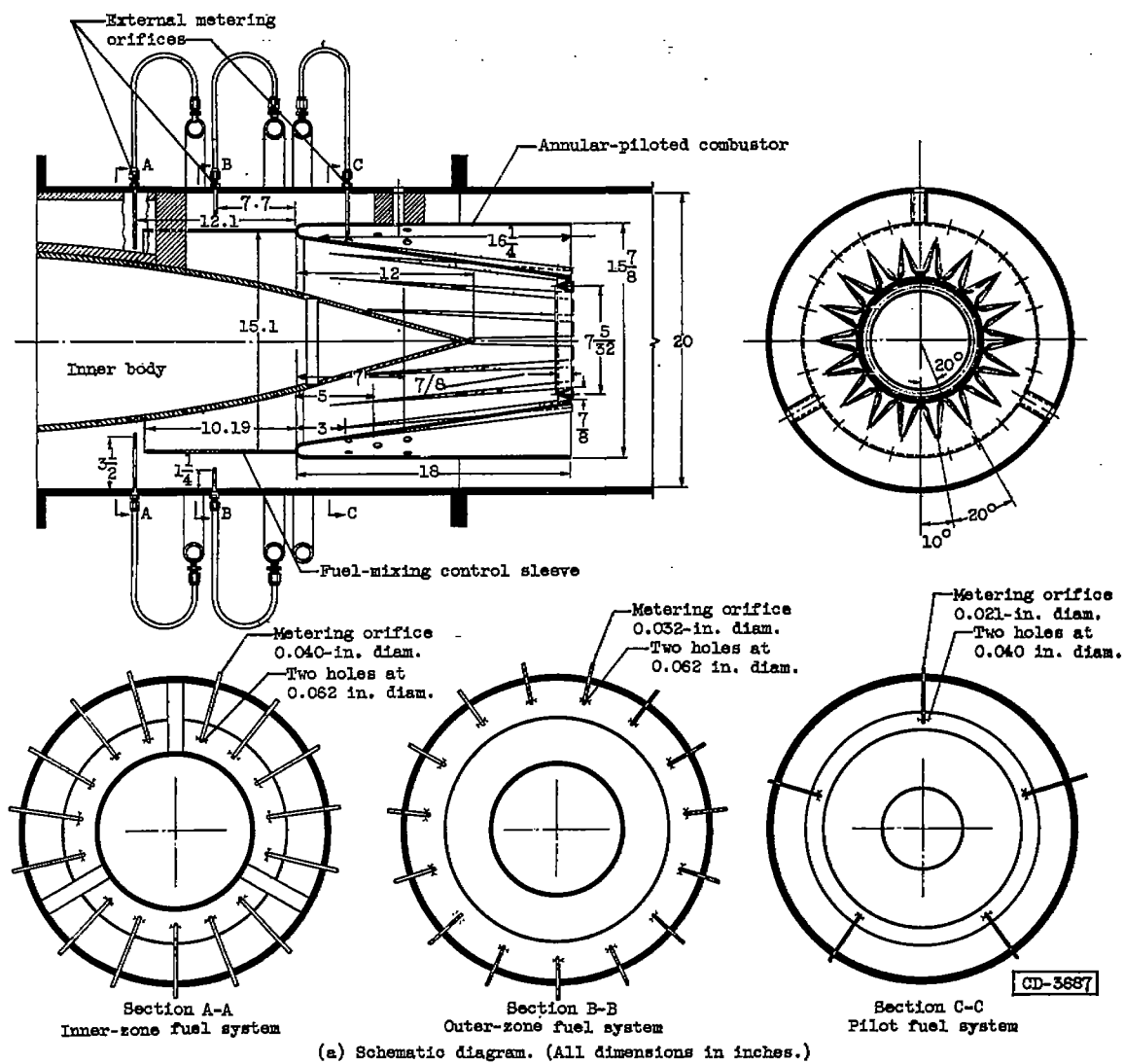
Figure 2. - Annular-piloted combustor.

Air flow

Air flow

CD-3690
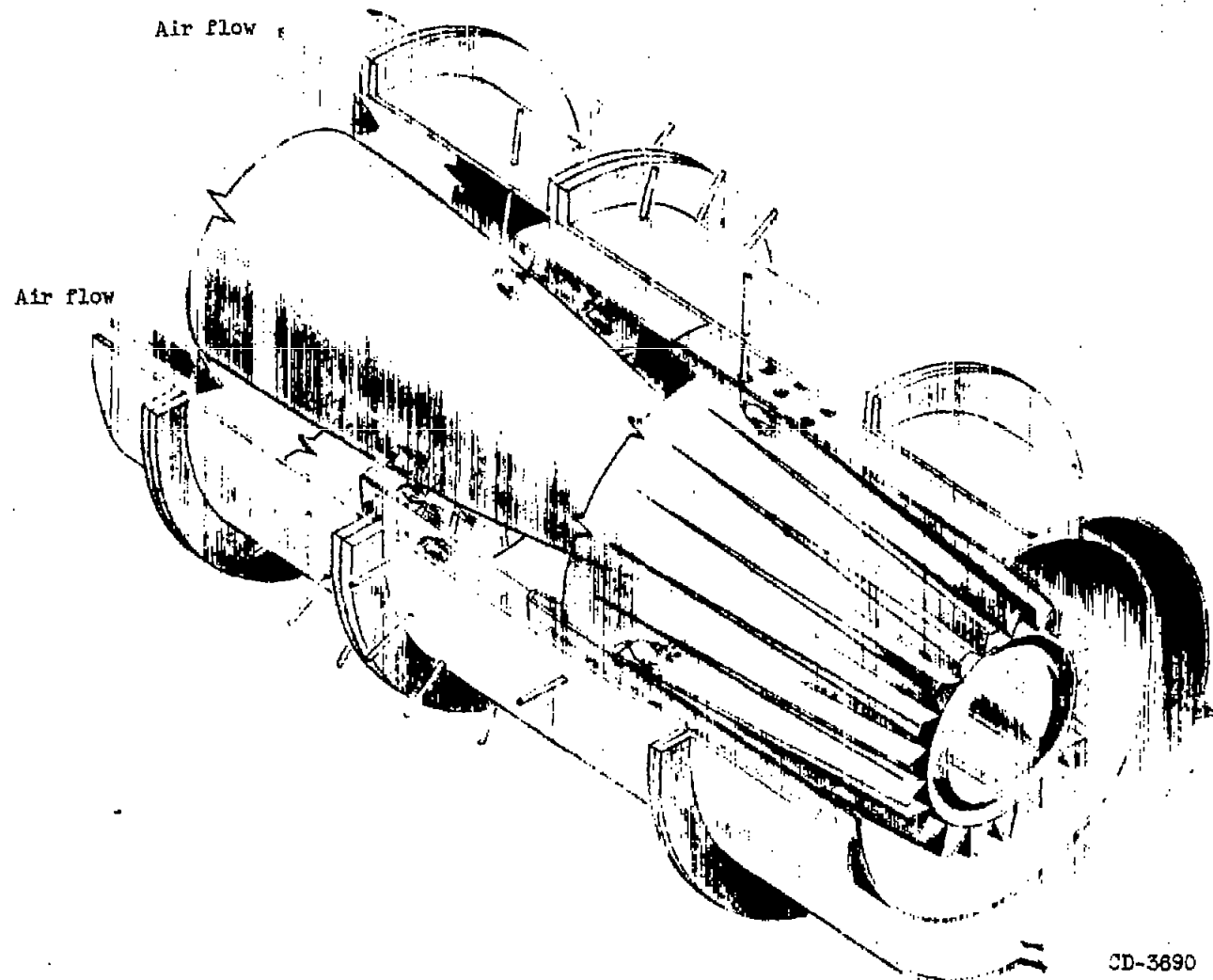
(b) Cutaway view.

Figure 2. - Continued. Annular-piloted combustor.
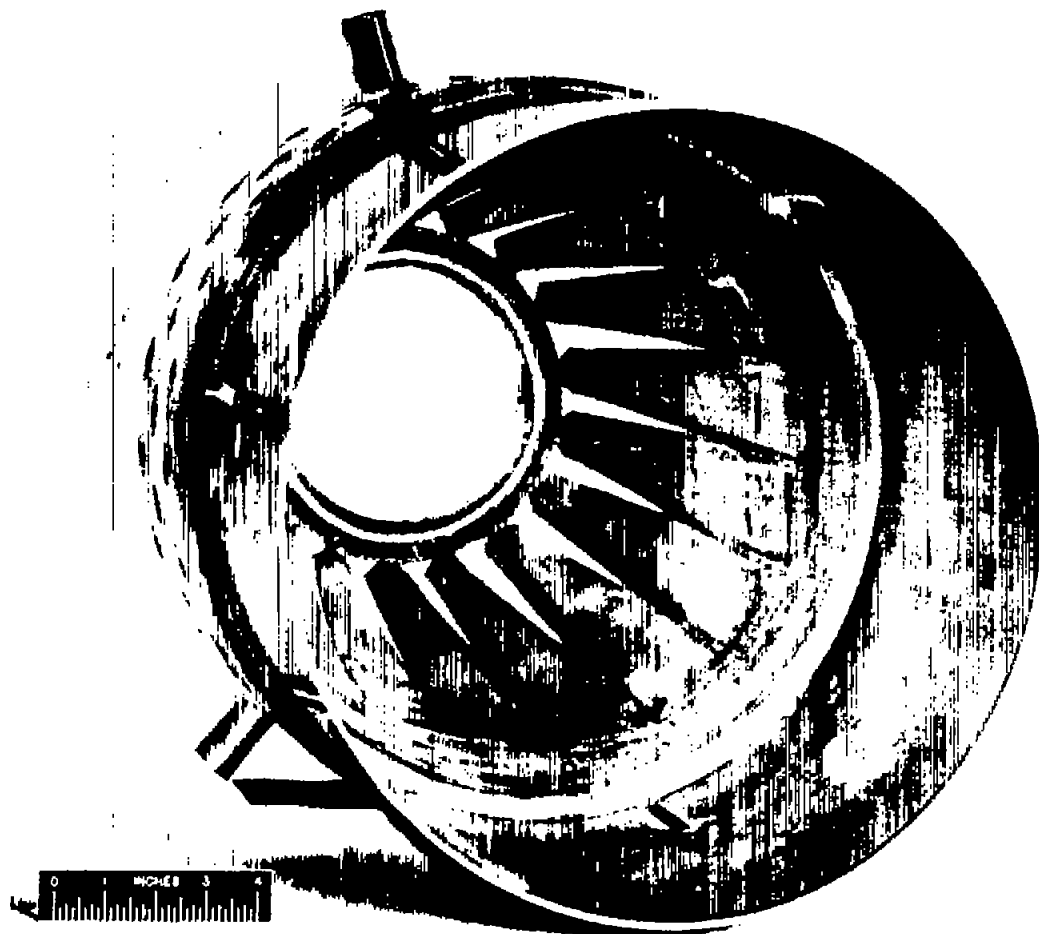
(c) View from upstream.

Figure 2. - Continued. Annular-piloted combustor.
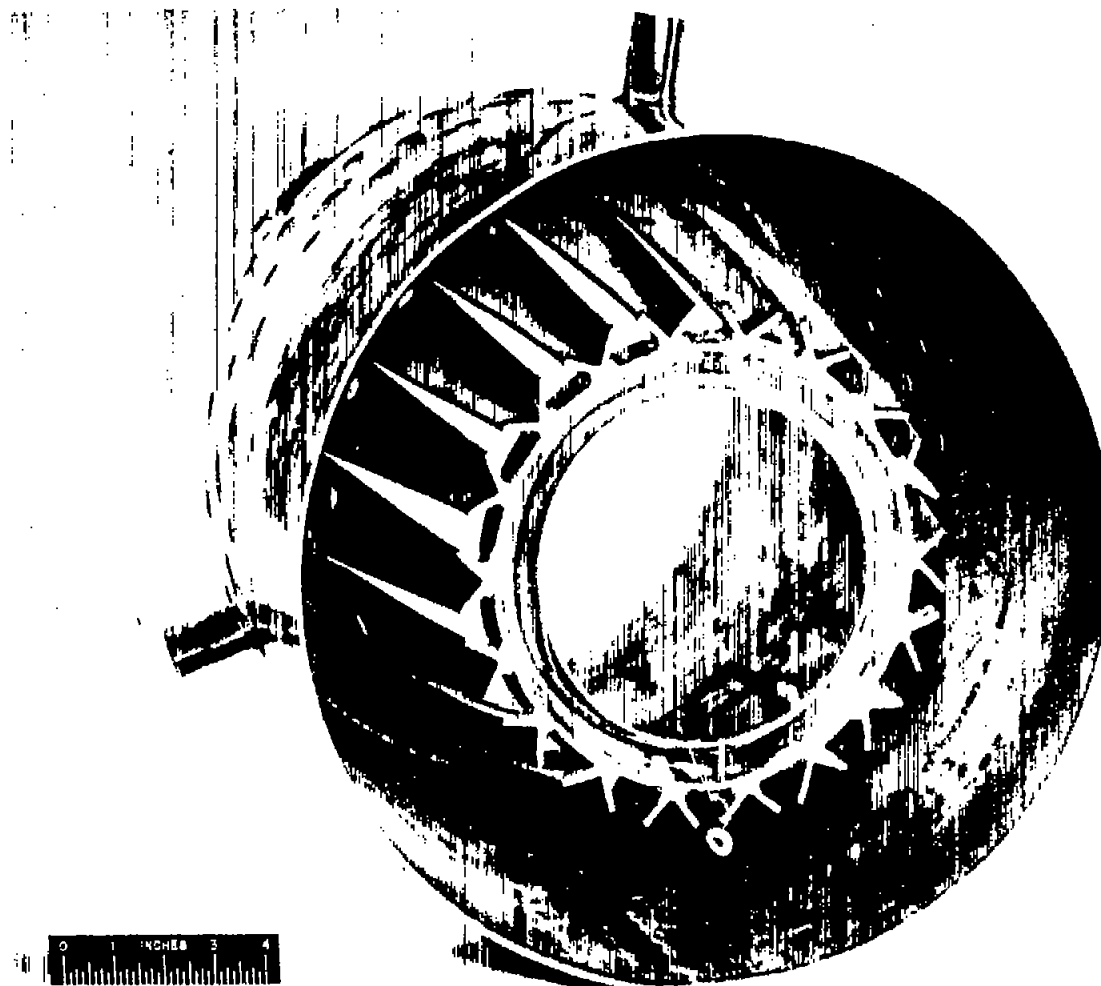
C-33798

(d) View from downstream.
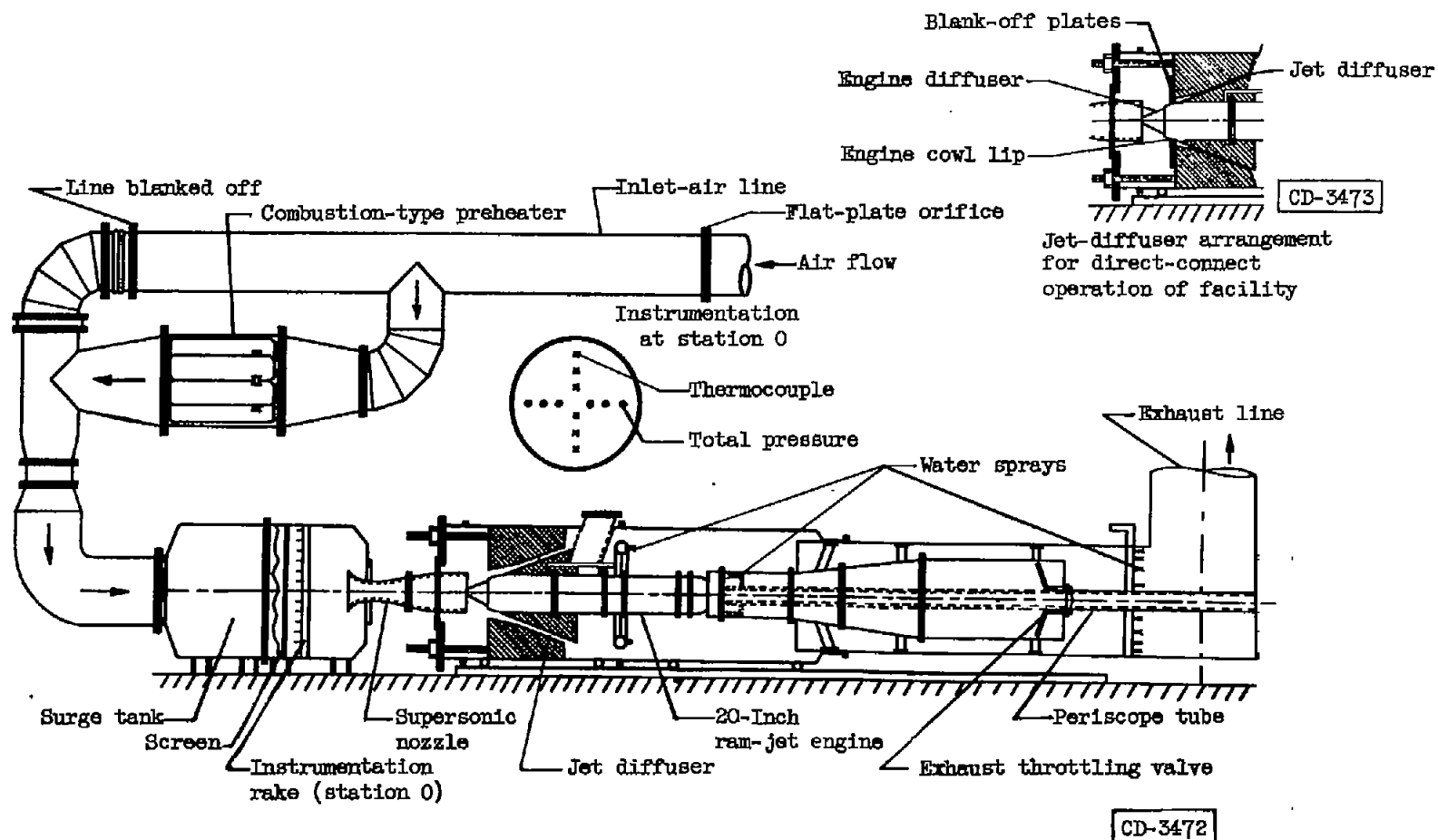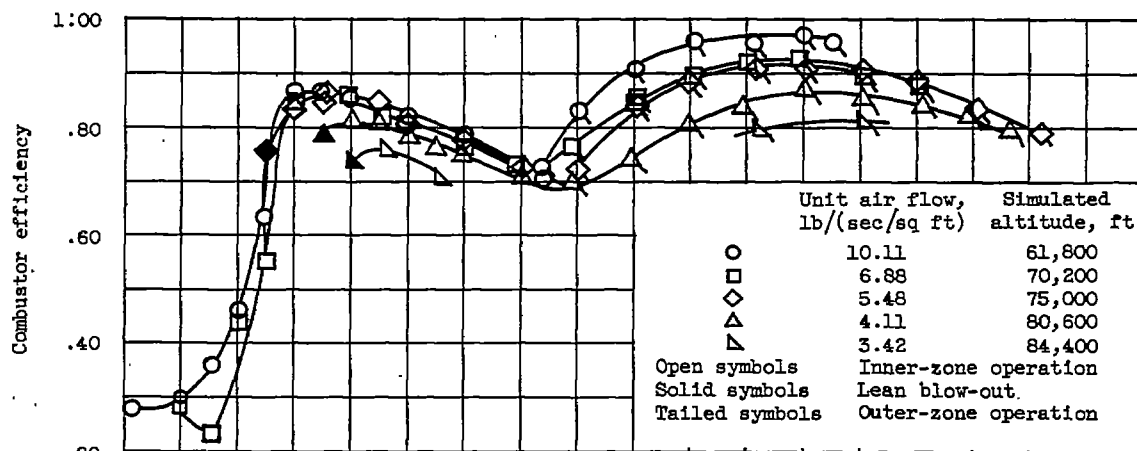
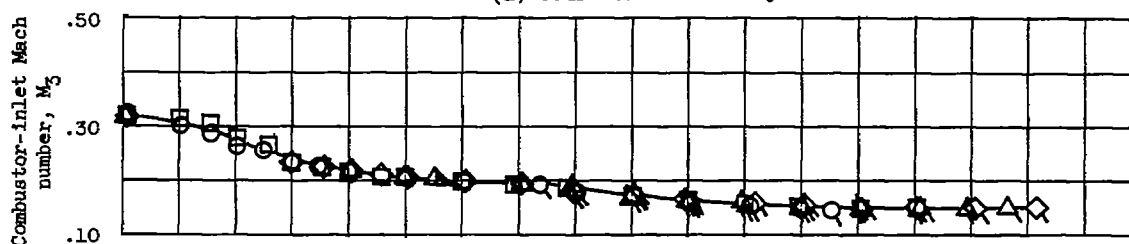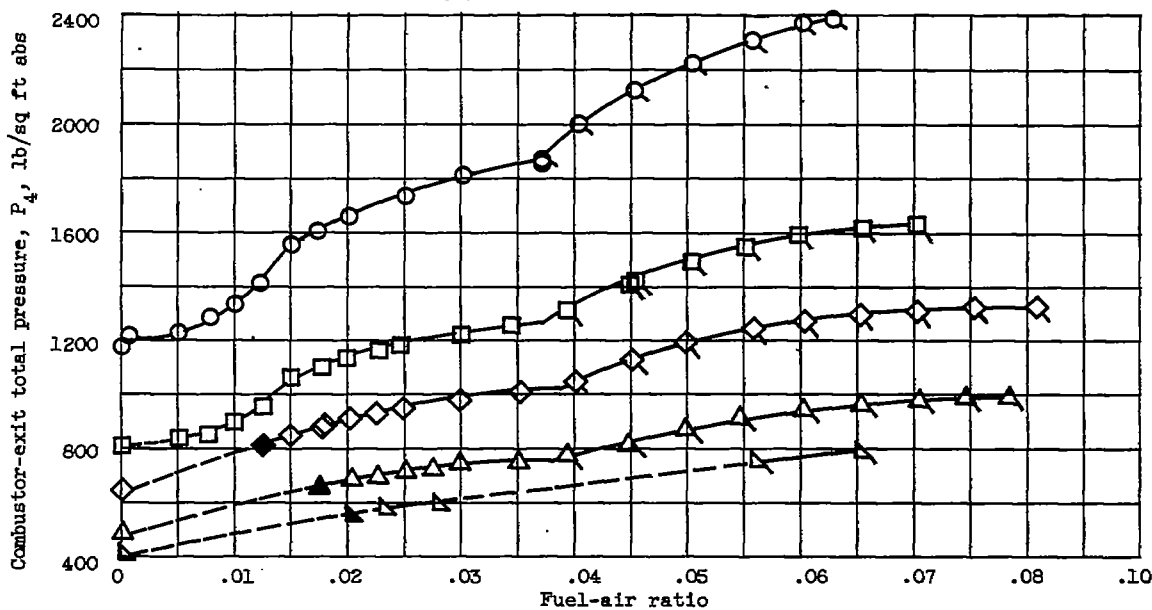Figure 2. - Concluded. Annular-piloted combustor.

C-33796

Blank-off plates

Engine diffuser

Jet diffuser

Engine cowl lip

CD-3473

Jet-diffuser arrangement
for direct-connect
operation of facility

Line blanked off

Combustion-type preheater

Inlet-air line

Flat-plate orifice

Air flow

Instrumentation
at station 0

Thermocouple

Total pressure

Water sprays

Exhaust line

Surge tank

Screen

Supersonic
nozzle

20-Inch
ram-jet engine

Periscope tube

Instrumentation
rake (station 0)

Jet diffuser

Exhaust throttling valve

CD-3472

Figure 3. - Free-jet facility with 20-inch-diameter ram-jet engine installed.

3377

(a) Combustor efficiency.

(b) Combustor-inlet Mach number.

(c) Combustor-exit total pressure.

Figure 4. - Performance of annular-piloted combustor. Mach number, 3.0; combustor length, 87 inches; free-jet data.
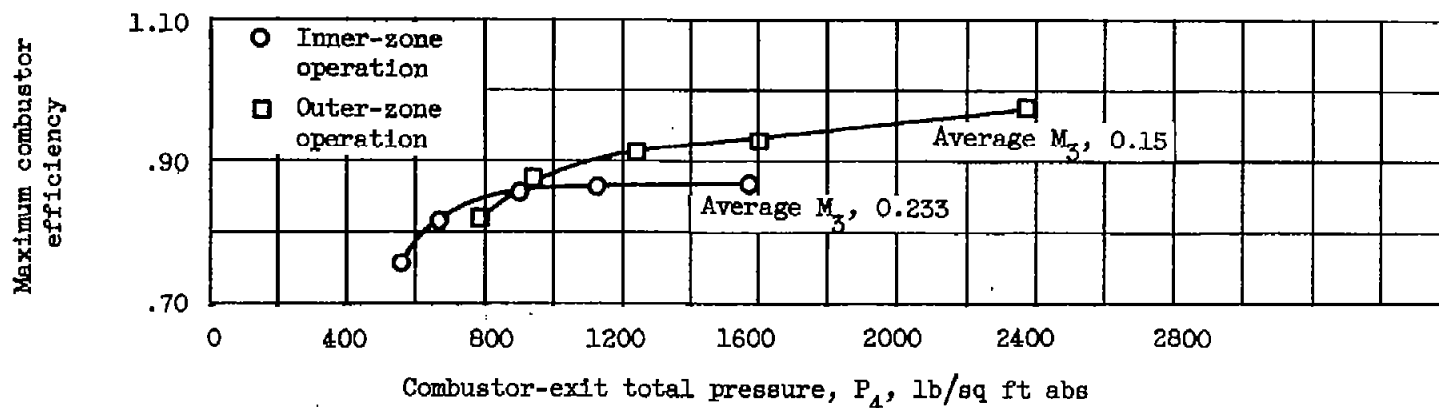
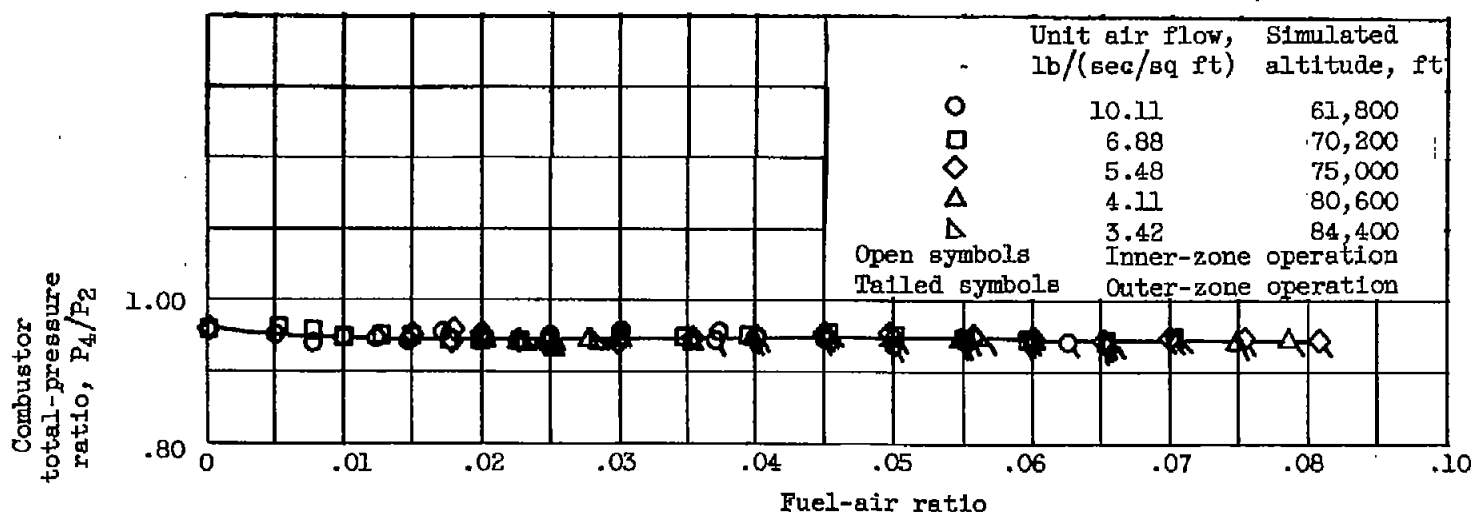Figure 5. - Variation of maximum combustor efficiency with combustor-exit total pressure. Free-jet data.

Figure 6. - Variation of combustor total-pressure ratio with fuel-air ratio. Combustor length, 87 inches; free-jet data.
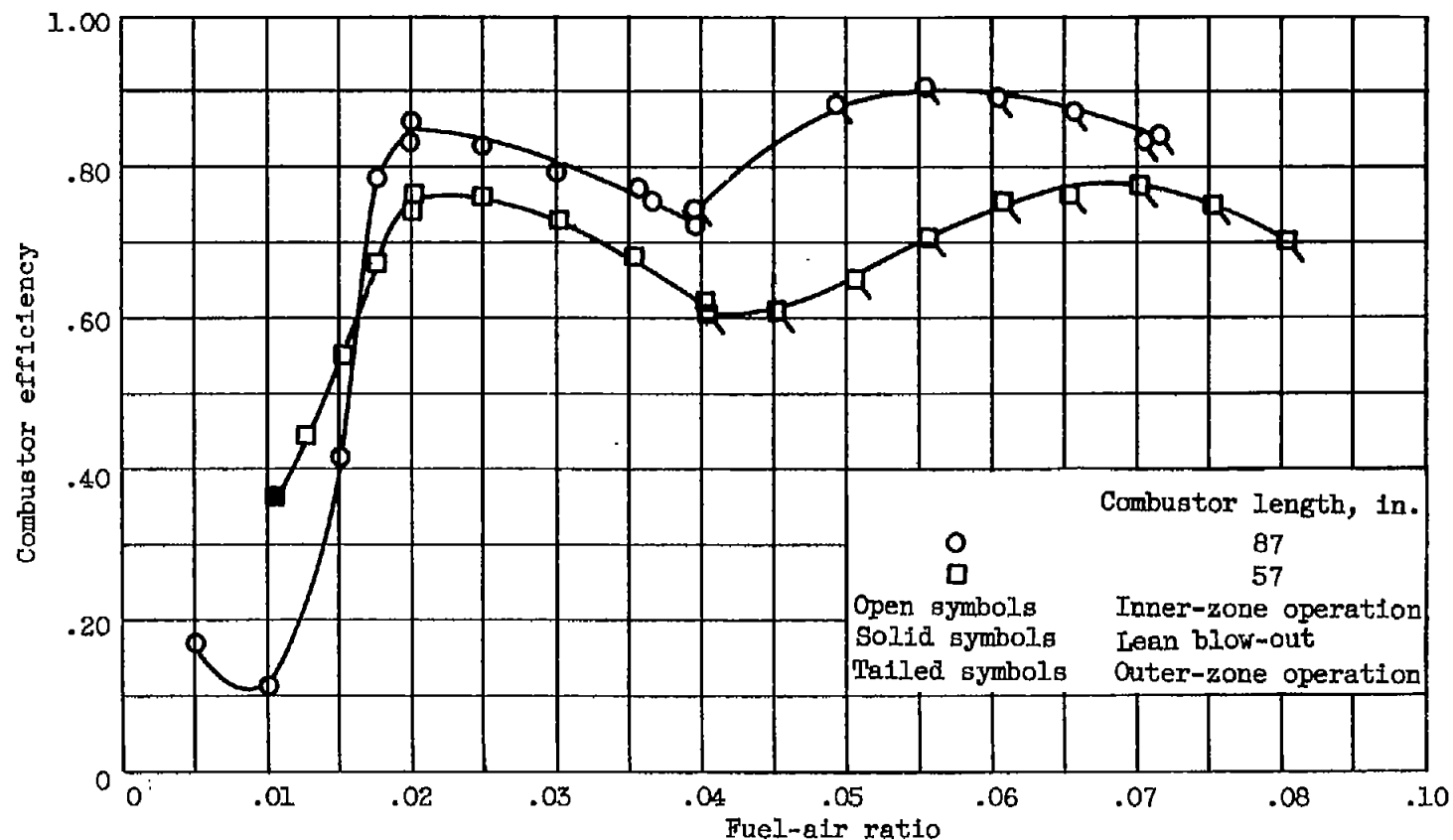
Figure 7. - Effect of combustion-chamber length on combustor efficiency of annular-piloted combustor. Unit air flow, 6.88 pounds per second per square foot of combustion-chamber cross-sectional area; corresponding simulated altitude, 70,200 feet; direct-connect data.
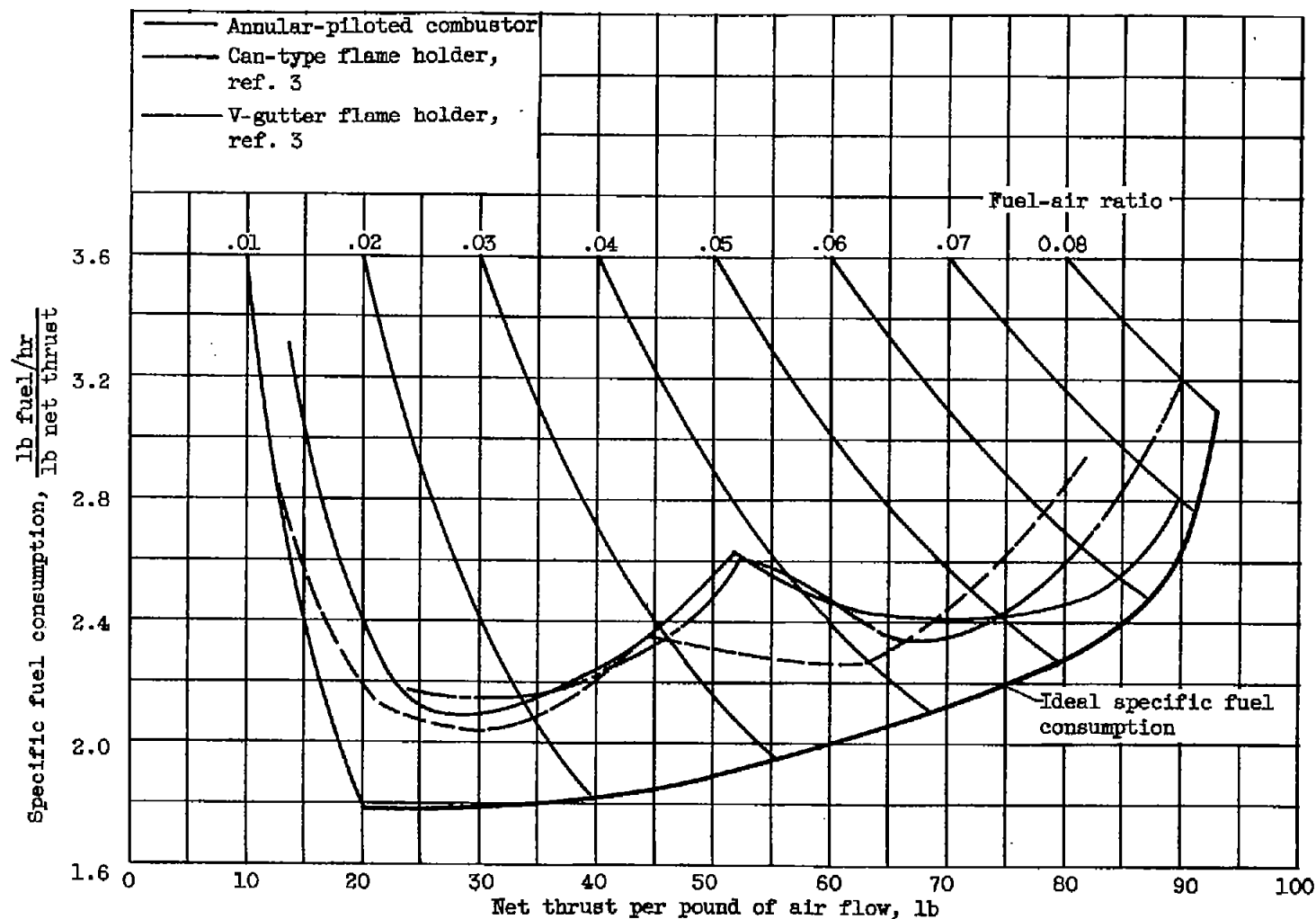
Figure 8. - Variation of specific fuel consumption with net thrust per pound of air flow. Diffuser total-pressure recovery, 0.6 (assumed); unit air flow, 6.88 pounds per second per square foot of combustion-chamber cross-sectional area; free-jet data.